Acceleration capabilities of nearby supermassive black holes

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Based on:
2020: Tursunov, et al. **Astrophysical Journal** 895:1, 14, arXiv:2004.07907
2019: Tursunov & Dadhich, **Universe**, 5, 125, arXiv:1905.05321
2018: Tursunov, et al. **Astrophysical Journal**, 861:2, arXiv:1803.09682
and some unpublished results

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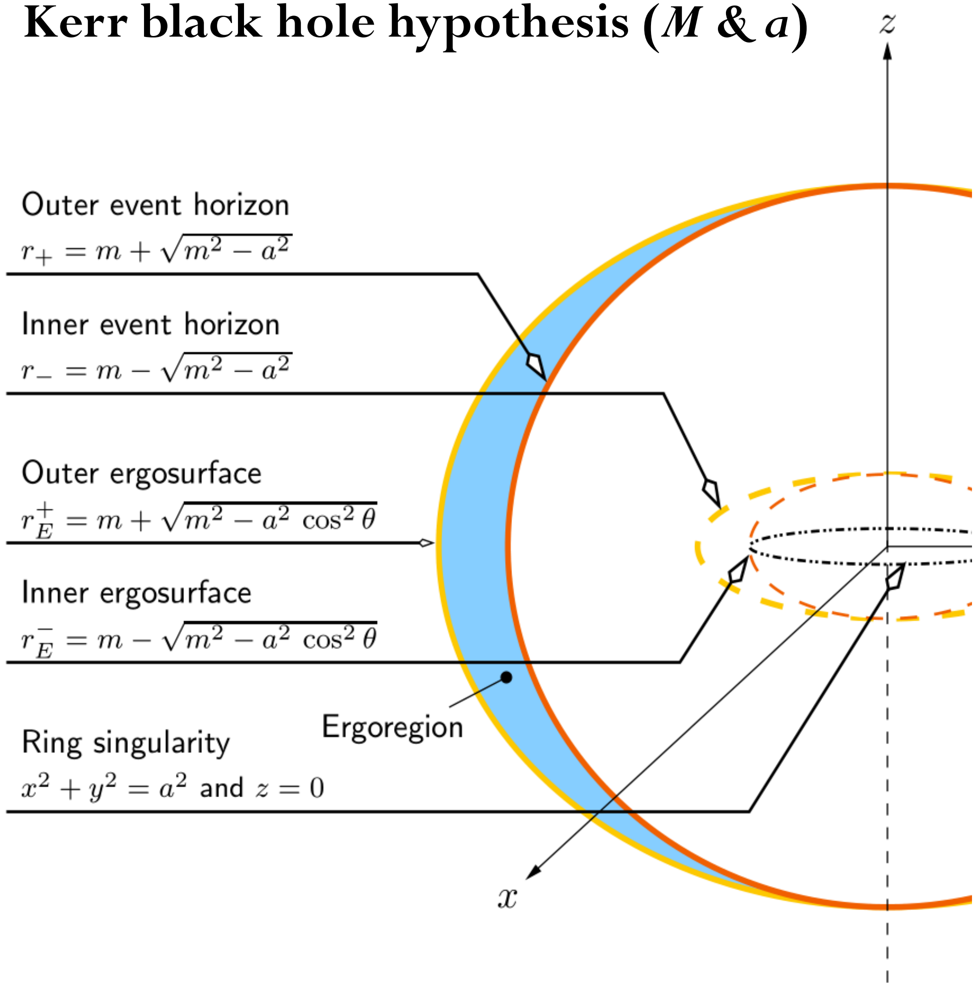
ZOOM / Opava

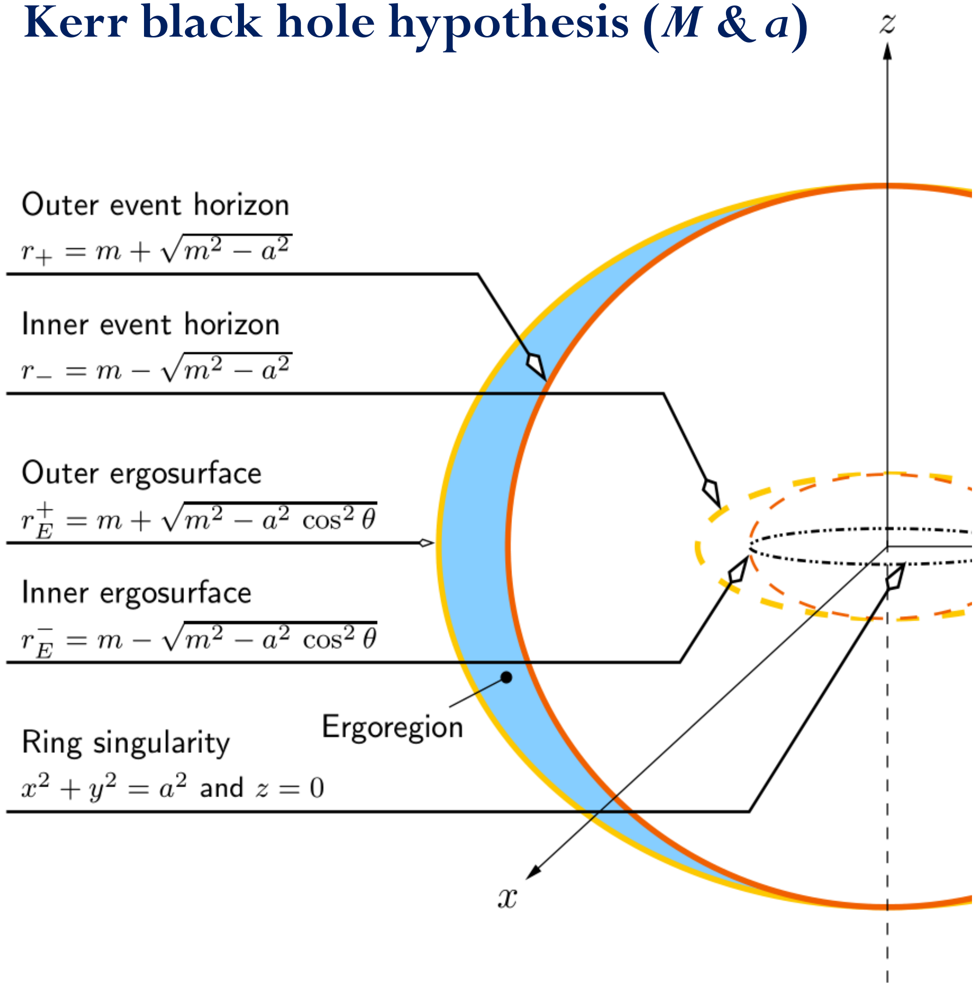
Rotating black hole as energy reservoir

Kerr black hole hypothesis (M & a)



Rotating black hole as energy reservoir

Kerr black hole hypothesis (*M* & *a*)



Entropy of black hole ~ to the event horizon area:

$$S_{\mathrm{BH}} = \frac{c^3}{4G\hbar} A_H$$

$$A_H = \int_0^{2\pi} d\phi \int_0^{\pi} \sqrt{\det g}\, d\theta = \frac{8\pi G}{c^2} M r_H$$

$$E_{\mathrm{irr}} = \sqrt{\frac{A_H}{16\pi G^2}} c^4 = \frac{Mc^2}{\sqrt{2}} \left[1 + \sqrt{1 - \left(\frac{a}{M}\right)^2} \right]^{\frac{1}{2}}$$

Energy extraction requires negative energy inflow

$$g_{tt} = \frac{2mr}{r^2 + a^2\cos^2\theta} - 1 \qquad \text{Ergosphere: } g_{tt} = 0$$

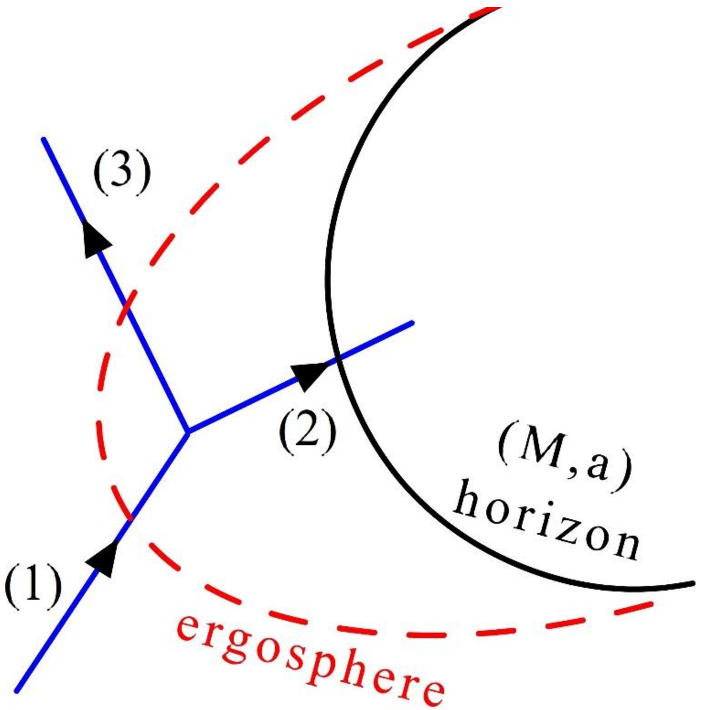
Inside the ergosphere g_{tt} changes its sign

$$E = -p_t = -mu_t = -mg_{tt}u^t - mg_{t\phi}u^\phi$$

Black hole mechanics and Thermodynamics have uncanny correspondence!
Black hole area non-decrease states that 29% of BH's energy is available for extraction.
For extremely rotating SMBH of 10^9 solar mass the available energy is 10^{74}eV

First energy extraction mechanism: Penrose process (1969)

Schematic plot of Penrose process



Conservation laws:

$$
\begin{aligned}
E_1 &= E_2 + E_3, \\
L_1 &= L_2 + L_3, \\
m_1\dot{r}_1 &= m_2\dot{r}_2 + m_3\dot{r}_3, \\
0 &= m_2\dot{\theta}_2 + m_3\dot{\theta}_3, \\
m_1 &\geq m_2 + m_3,
\end{aligned}
$$

$$m_1 u_1^{\phi} = m_2 u_2^{\phi} + m_3 u_3^{\phi}.$$

Efficiency of Penrose process:

$$\eta = \frac{E_3 - E_1}{E_1} = \frac{-E_2}{E_1}.$$

After several algebraic manipulations and setting

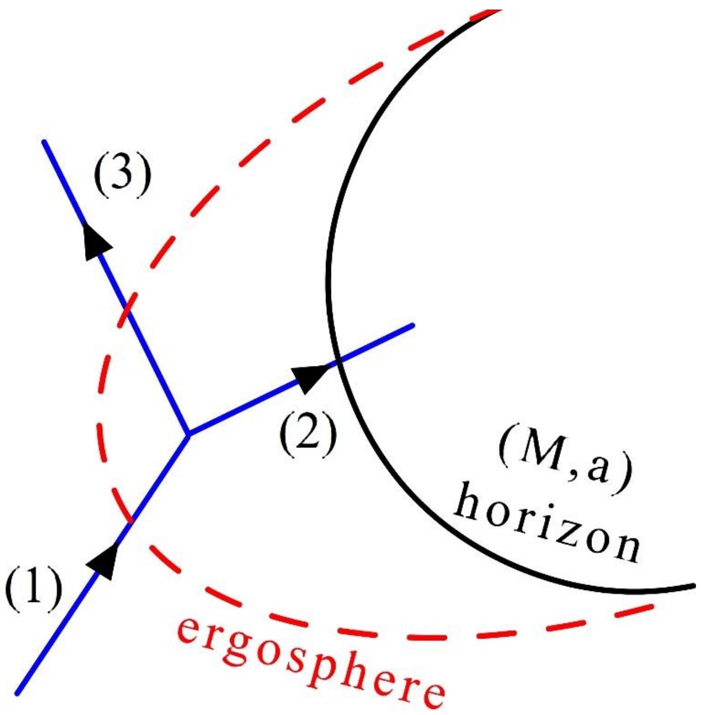
$$\Omega_1 = \Omega, \quad \Omega_2 = \Omega_-, \quad \Omega_3 = \Omega_+$$

$$\boxed{\eta = \frac{1}{2}\left(\sqrt{1 + g_{tt}}) - 1\right)}$$

Maximum efficiency of Penrose process is 21%

Historical development of the idea

Original Penrose process



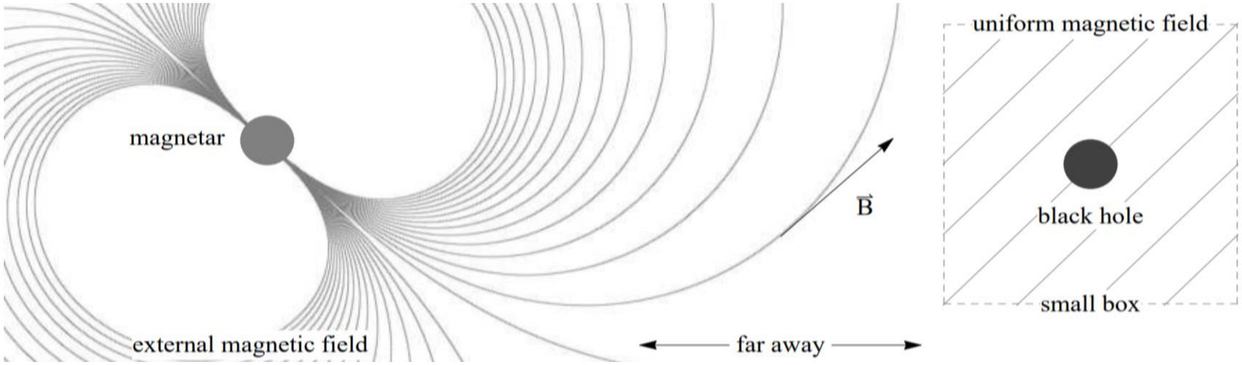
Efficiency is defined as:

$$\eta = \frac{E_3 - E_1}{E_1} = \frac{-E_2}{E_1}.$$

- Penrose (1969) – the energy can be extracted with the **efficiency** limited to 20.7%
- Bardeen et al. & Wald (1972, 1974) – Penrose process **is unrealizable** in astrophysical conditions.
- Piran et al. (1975/77) – Collisional Penrose process
- Ruffini & Wilson (1975) – Electromagnetic energy extraction by charge separation in **accreting magnetized plasma**
- Blandford & Znajek (1977) & later numerous MHD simulations – **efficiency** up to few 100%
- Wagh et al. (1985) – Electromagnetic version of Penrose process – **efficiency can exceed** 100%
- Many other versions of above mentioned processes with different **efficiencies** of up to few 100%
- Tursunov et al. (2019, 2020) – efficiency $> 10^{10}\%$ for protons in case of SMBHs

Black holes are weakly magnetized

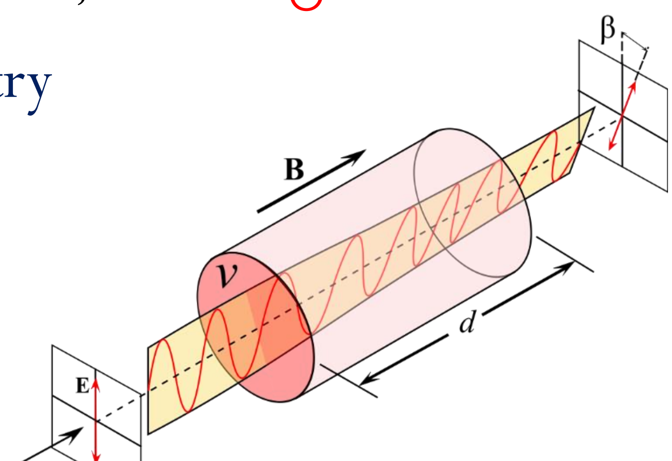
- Dynamics of surrounding plasma or accretion disk of BH
- Magnetic field of the companion or collapsed progenitor star



e.g. Magnetar with 10^{14}G has been found at 0.3 light years from Galactic Center by Effelsberg observatory

- MF of **SgrA* ~ 10G**. Characteristic MF for $10^9 M_\odot$ is 10^4G; for $10 M_\odot$ can exceed 10^8G.
- MF is weak – it does not modify the spacetime geometry

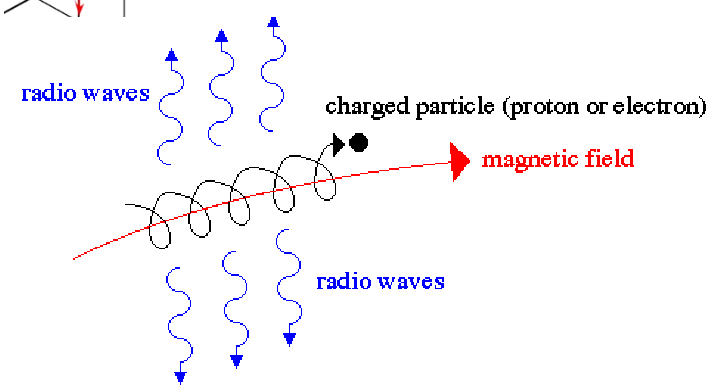
$$B \ll \frac{c^4}{G^{3/2} M_\odot} \left(\frac{M_\odot}{M}\right) \sim 10^{19} \frac{M_\odot}{M} \text{ G}$$



- Cannot neglect **MF effects** on the charged matter

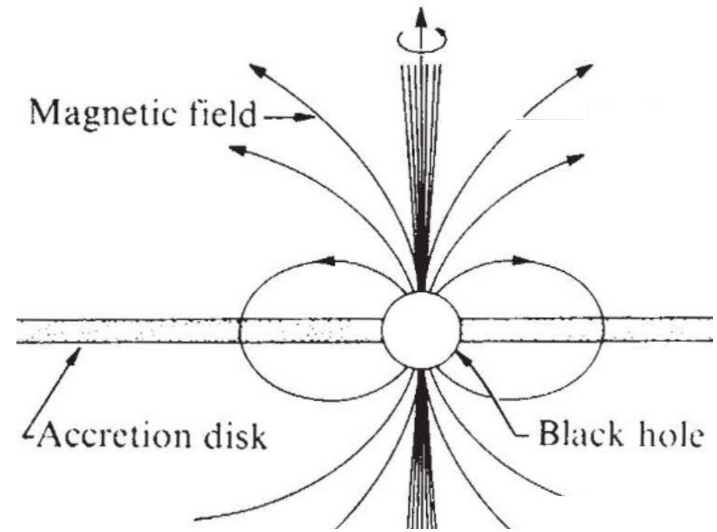
$$\frac{F_{\text{lorentz}}}{F_{\text{grav.}}} = \frac{eBGM}{m_p c^4} \approx 10^{11} \left(\frac{B}{10^4 \text{G}}\right) \left(\frac{M}{10^9 M_\odot}\right)$$

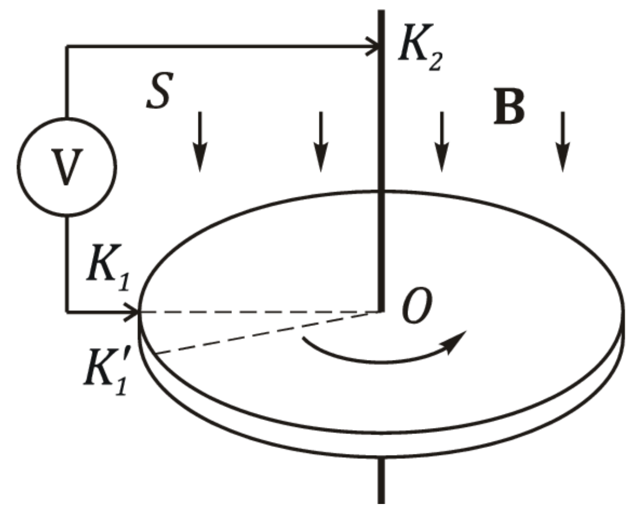
- This ratio for **SgrA* ~ 10^6**
- Measurements: Faraday rotation, synchrotron radiation, etc.



Black holes are weakly charged

- **Assume that MF shares spacetime symmetries**
  - $A^{\phi} \neq 0$ implies that $A_{\phi} = g_{\phi\phi} A^{\phi}$ and $A_t = g_{t\phi} A^{\phi}$, i.e. **electric field is induced**
  - This will cause a **selective accretion** into BH and consequent **NET-charging of BH**.
- **Solution of Maxwell eqs. for uniform MF**
  - $A_t = \frac{B}{2}(g_{t\phi} + 2a g_{tt}), \qquad A_{\phi} = \frac{B}{2}(g_{\phi\phi} + 2a g_{t\phi}).$
  - $\Delta\varphi = \varphi_{\mathrm{H}} - \varphi_{\infty} = \frac{Q - 2aMB}{2M}.$ (Wald, 1974)
  - Potential difference is neutralized by accretion until **BH accretes positive net charge** $2aMB$
  - Therefore, there are two solutions:
    1) **BH with zero charge** (formal mathematical solution)
    2) **BH with net electric charge** (physical solution)
  - SgrA* charge is **$< 10^{15}$ C** (Zajacek, et al., 2018,19,20)
- **Magnetosphere is charged as well**
  - In a similar way, rotation of BH in MF induces EF and BH with the **magnetosphere acts as dynamo**!
  - $Q_{\mathrm{mag}} = -Q_{\mathrm{BH}}.$



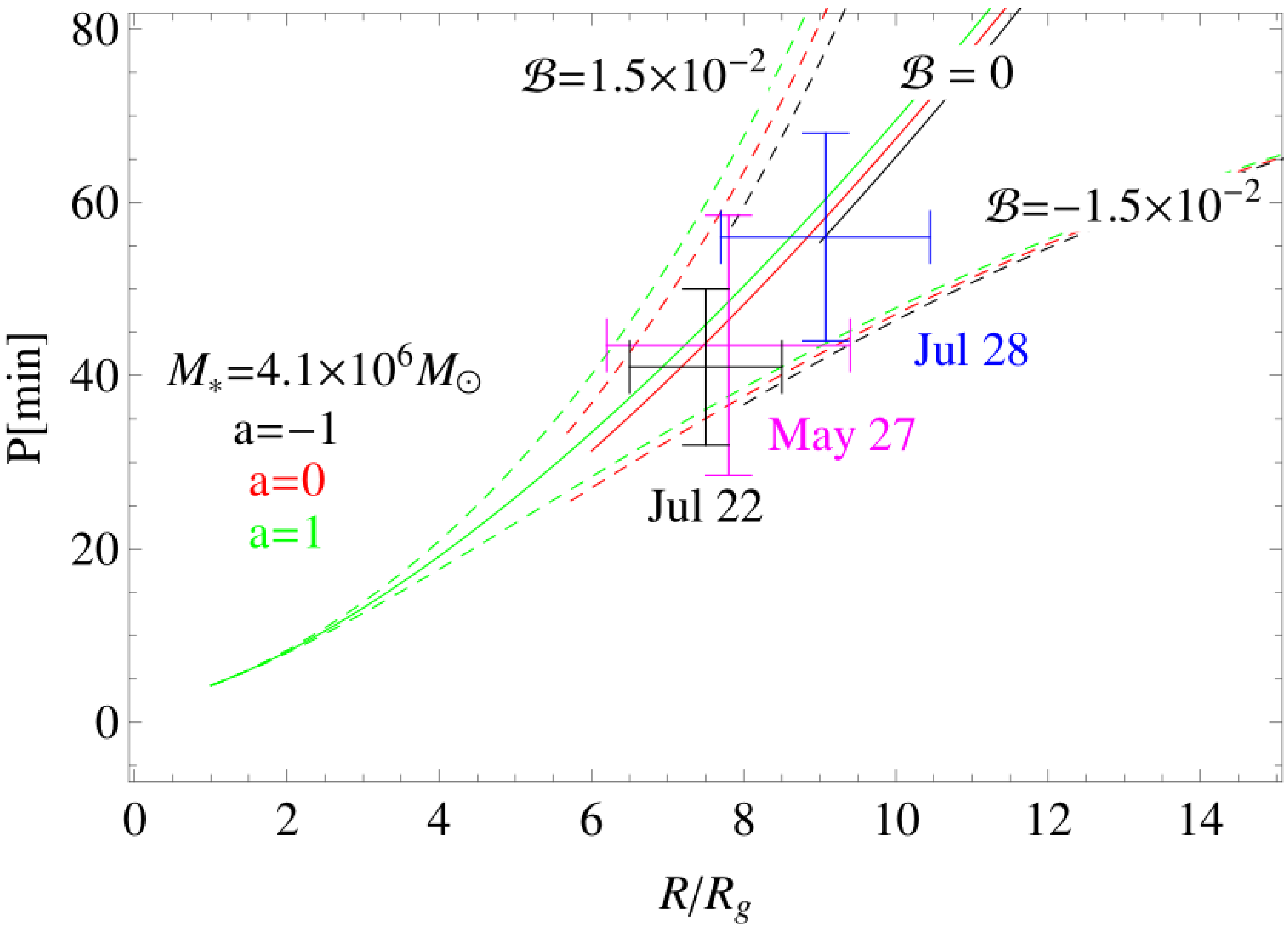


$\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$

Dynamics of the flare components

Given the nonzero net charge density from charge separation in a plasma, one can get upper and lower limits on the Lorentz force $10^{-5} < \frac{F_{\rm Lor.}}{F_{\rm grav.}} \equiv \mathcal{B} < 10.$

Tighter constraints we get from GRAVITY flares fitting



$$-0.015 < \mathcal{B} < 0.01.$$

$$\mathcal{B} = \frac{q_{\rm hs}\, G\, B\, M_{\bullet}}{2\, m_{\rm hs}\, c^4},$$

$$\frac{|q_{\rm hs}|}{m_{\rm hs}} < 10^{-3} \left(\frac{B}{10{\rm G}}\right)^{-1} {\rm C/g},$$

$$\frac{N_{\rm charged}}{N_{\rm neutral}} = \frac{q_{\rm hs}}{e} \frac{m_{\rm p} + m_{\rm e}}{m_{\rm hs}} < 10^{-8}$$

Tursunov et al., ApJ (2020)

Energy extraction regimes

- Integrals of motion: $-E = mu_t + qA_t \qquad L = mu_\phi + qA_\phi$
- Conservation laws: $E_1 = E_2 + E_3,\ L_1 = L_2 + L_3,$

$$q_1 = q_2 + q_3,\ m_1 \geq m_2 + m_3,$$

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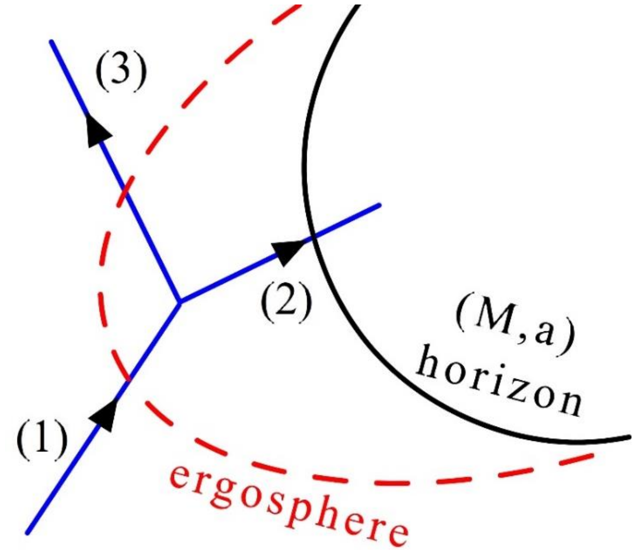
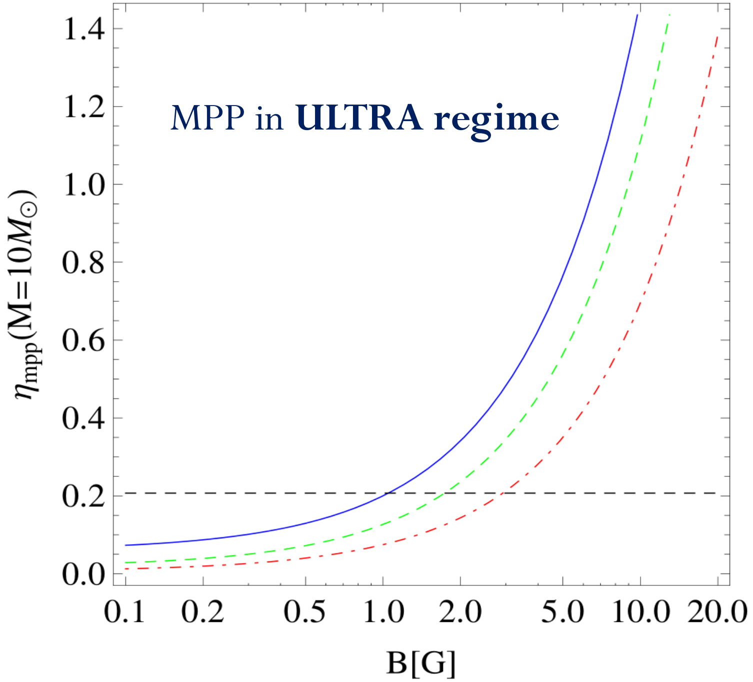


- Efficiency definition: $\eta = \dfrac{E_3 - E_1}{E_1} = \dfrac{-E_2}{E_1}.$
- Result: $\eta_{\text{MPP}} = \chi - 1 + \dfrac{\chi\, q_1 A_t - q_3 A_t}{E_1},\quad 1 \leq \chi \leq 1.21$, for spin $0 \leq a \leq 1$.

- There exist 3 regimes of BH energy extraction: **Low, Moderate and Ultra**

1. Low: Penrose limit **< 0.21** **(neutral matter)** $\eta_{\text{PP}} = \dfrac{1}{2}\left(\sqrt{\dfrac{2M}{r}} - 1\right).$
2. Moderate: same as BZ **< 10** **(charged matter)** $\eta_{\text{MPP}}^{\text{mod.}} \approx \dfrac{q_3}{q_1} - 1.$
3. Ultra: novel regime **$> 10^9$** **(ionization of neutral matter)** $\eta_{\text{MPP}}^{\text{ultra}} \approx \dfrac{q_3}{m_1} A_t.$



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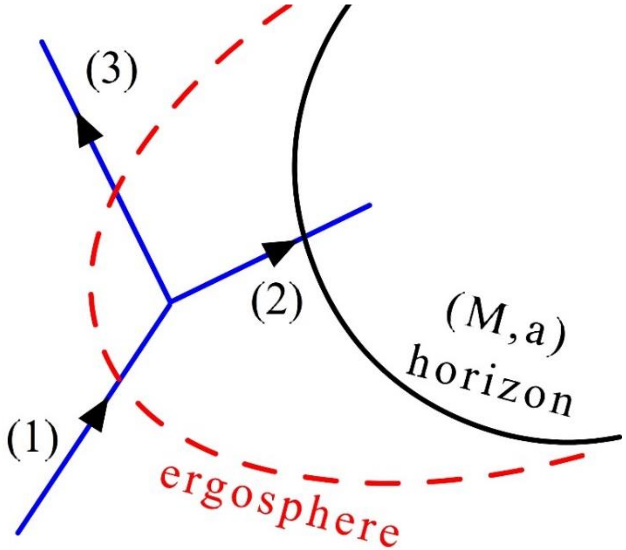

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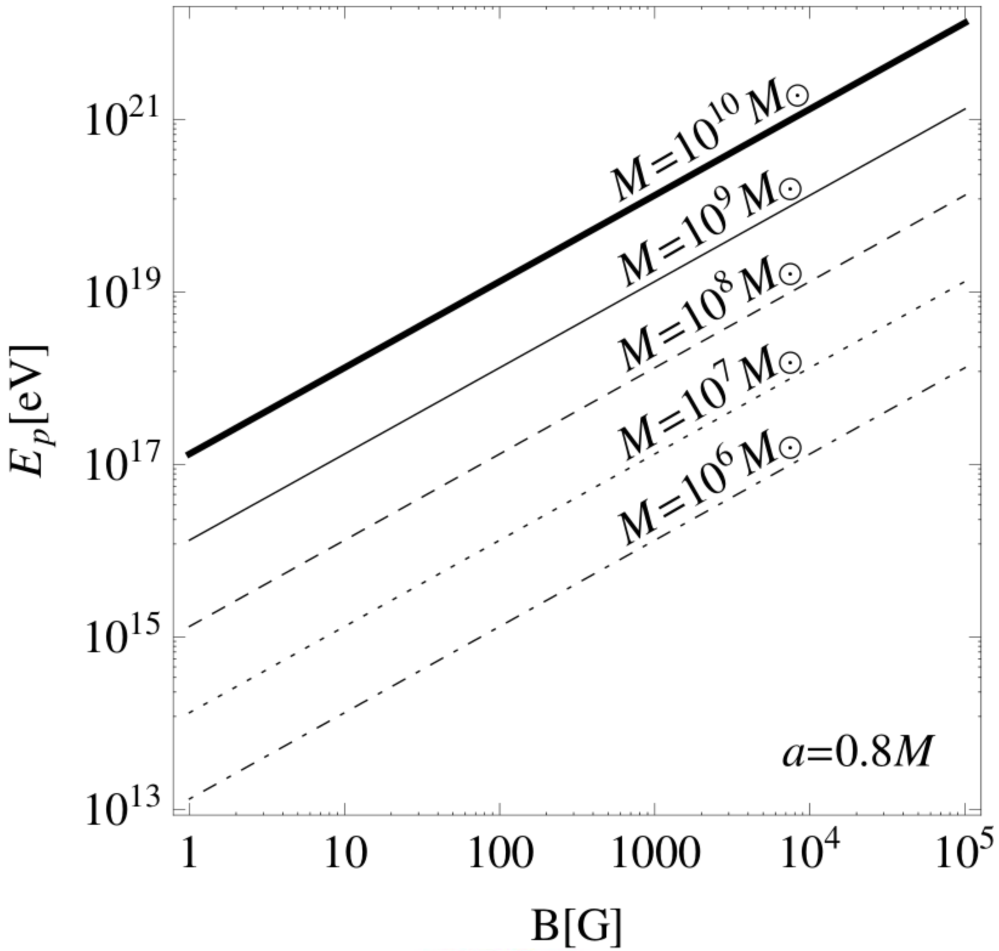
2. Moderate: same as BZ **< 10 (charged matter)** $\quad \eta^{\text{mod.}}_{\text{MPP}} \approx \dfrac{q_3}{q_1} - 1.$
3. Ultra: novel regime **> 10^9 (ionization of neutral matter)** $\quad \eta^{\text{ultra}}_{\text{MPP}} \approx \dfrac{q_3}{m_1} A_t.$

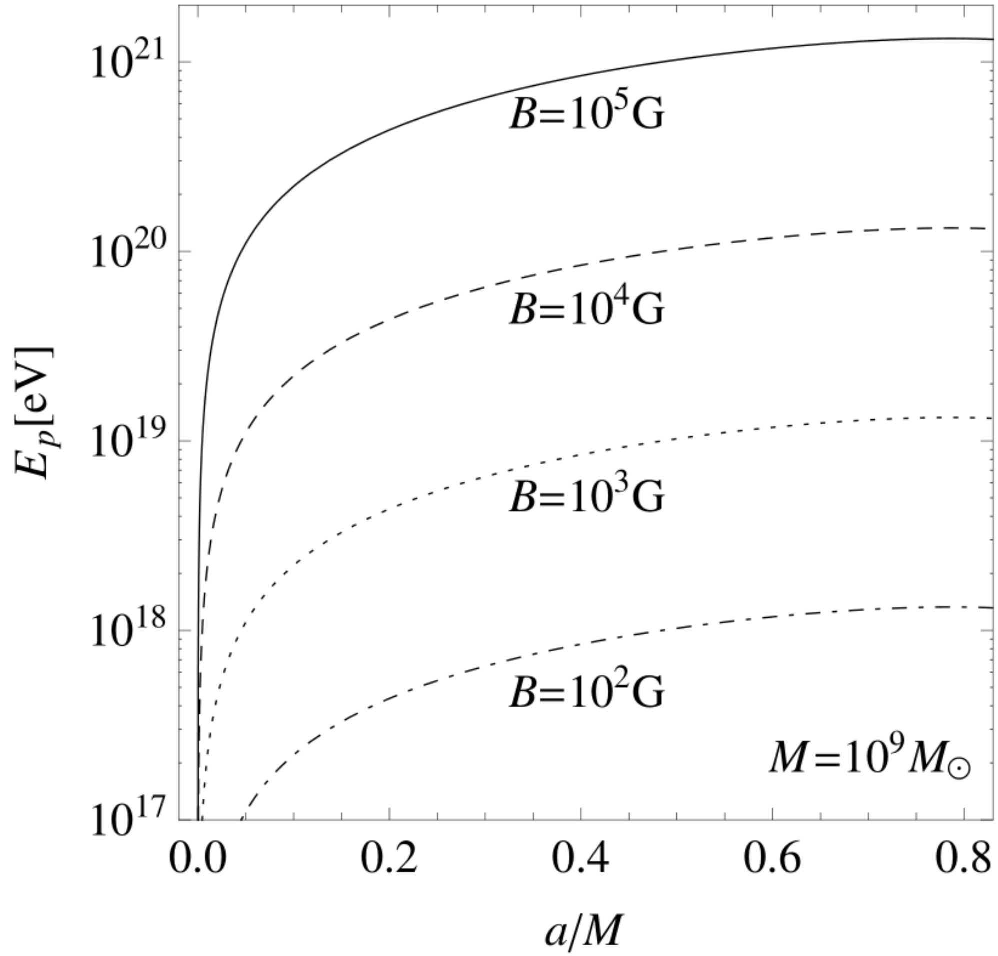
Let us consider the two ionization processes around Kerr BH of $10 M_\odot$ mass and 10^4G MF:

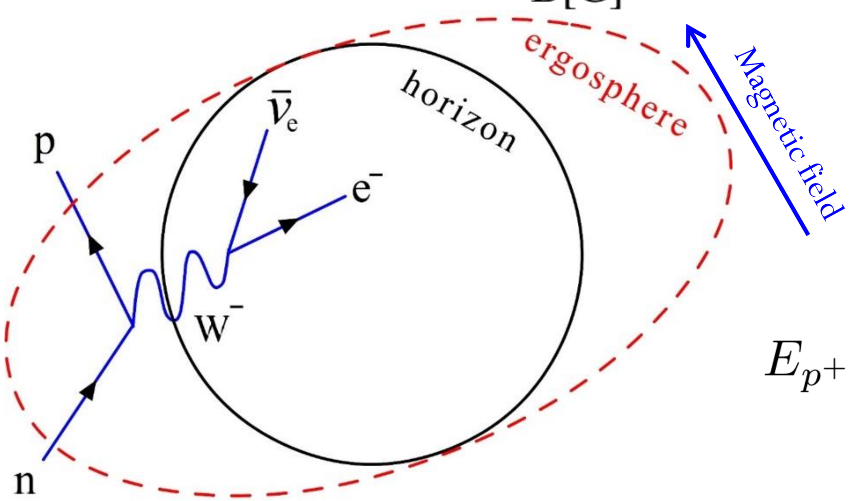
$$\text{He}^+ \to \alpha(\text{He}^{++}) + e^-. \quad \boxed{\eta^{\text{mod}}_{\text{He}^+} = 0.99.}$$

$$\text{He} \to \alpha(\text{He}^{++}) + 2e^-, \quad \boxed{\eta^{\text{ultra}}_{\text{He}} = 2.4 \times 10^3}$$

Energy of proton driven away from BH







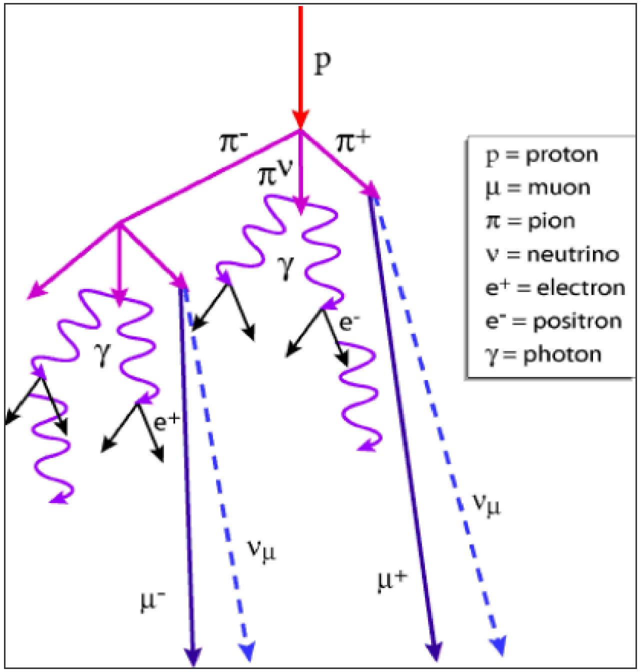
Energy of free neutron is $\sim 0.94 \times 10^9$eV

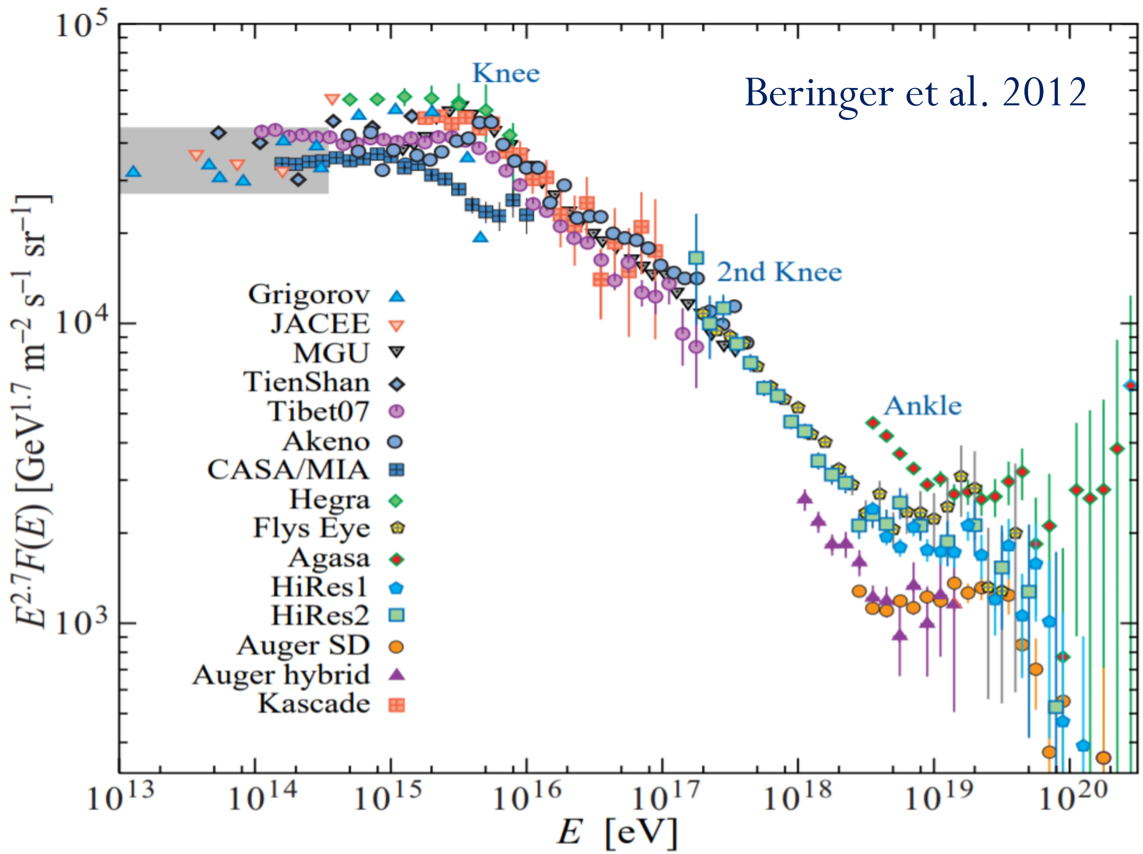
Energy of escaping proton after neutron beta decay:

$$E_{p^+} = 1.33\times10^{20}\text{eV}\left(\frac{q}{e}\right)\left(\frac{m}{m_{p^+}}\right)^{-1}\left(\frac{B}{10^4\text{G}}\right)\left(\frac{M}{10^9 M_\odot}\right).$$

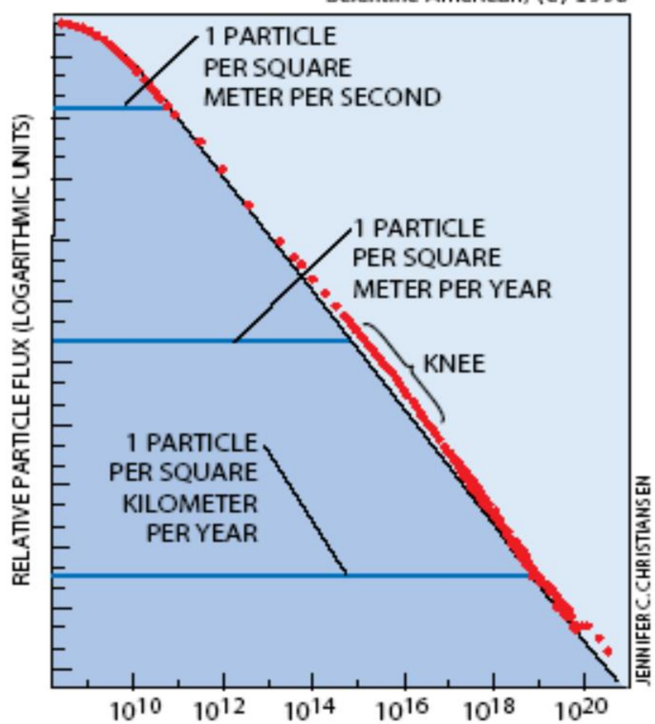
Application: Ultra-High-Energy Cosmic Rays

- Few things we know about UHECRs:
  - Unreachable energy by Earth based experiments
  - These are charged particles
  - Spectrum has knees and ankle
  - Extremely rare at ultra-high energies
  - Extra-Galactic origin
  - Detected mainly on Earth – composition at high energy is ?
- Mechanism is unknown – most energetic accelerator in the universe!





Scientific American, (c) 1998



The Milky Way's SgrA* as PeVatron

- **Mass is $\sim 4 \times 10^6 M_\odot$**
- **Spin is loosely constrained**
- **External magnetic field**

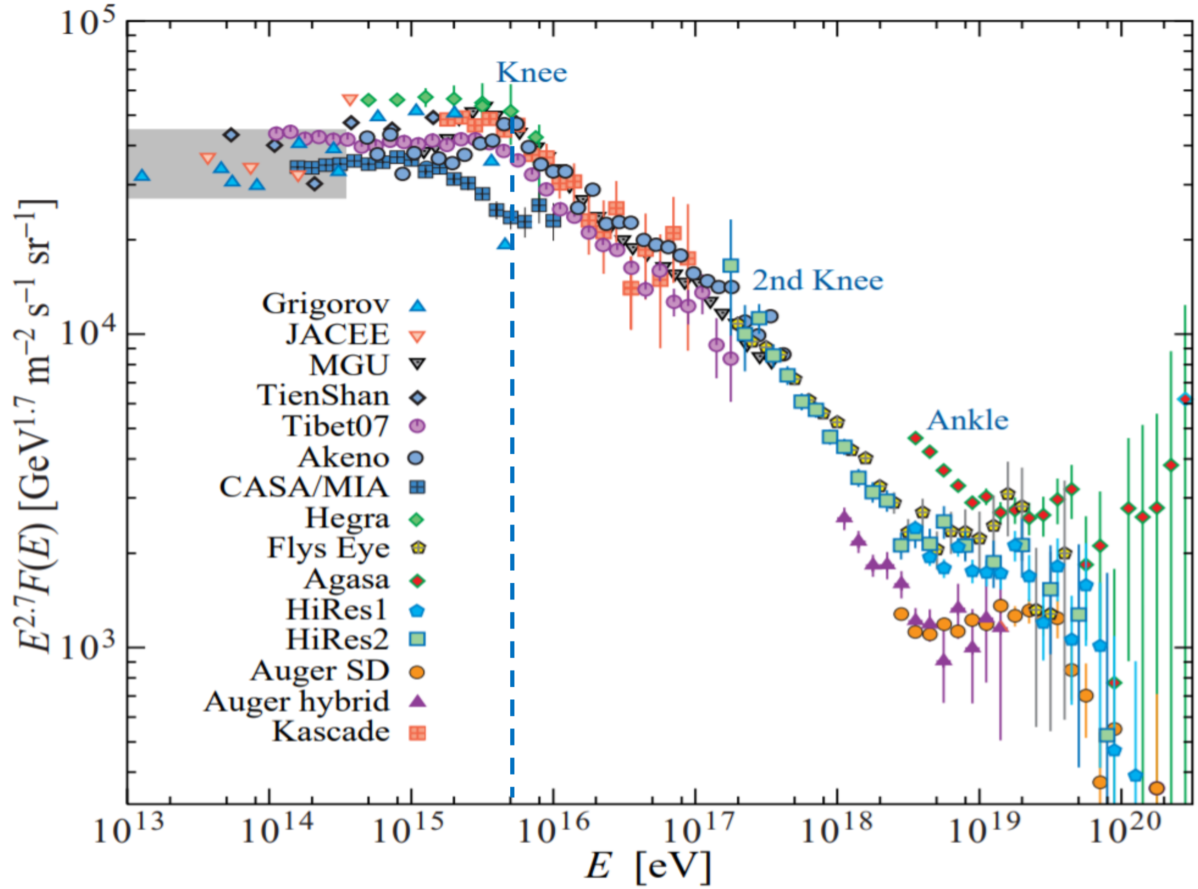
– near horizon $\sim 10 - 100$ G

- **SgrA* charge $< 10^{15}$ C**

– gain Coloumb contribution

- **Infalling matter**

– neutral particle ionization



Applying ultra-MPP

$$n^0 \rightarrow p^+ + W^-$$

$$E_n = E_p + E_W,$$

$$L_n = L_p + L_W,$$

$$m_n \dot{r}_n = m_p \dot{r}_p + m_W \dot{r}_W,$$

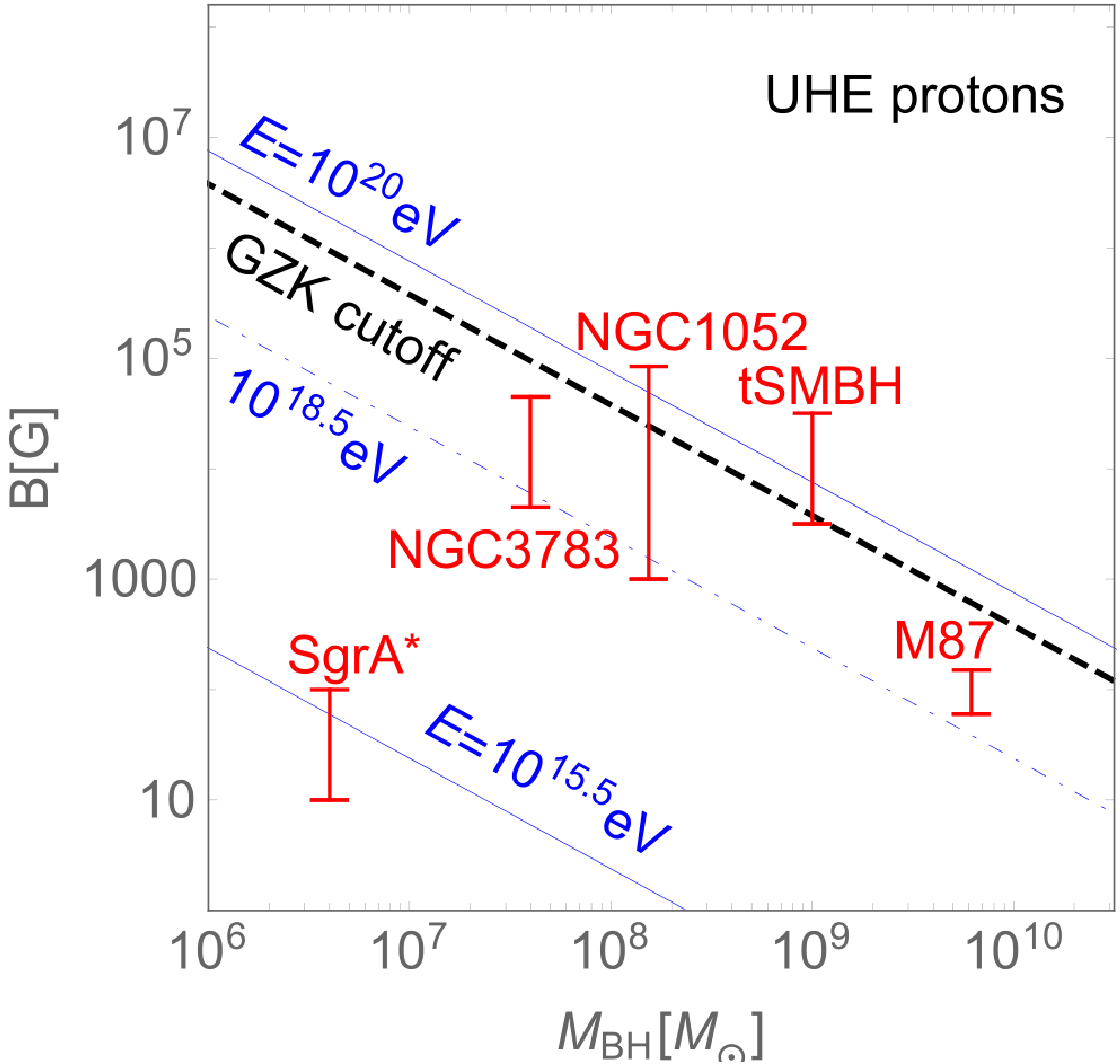
$$q_W + q_p = 0.$$

Proton energy corresponds to the Knee

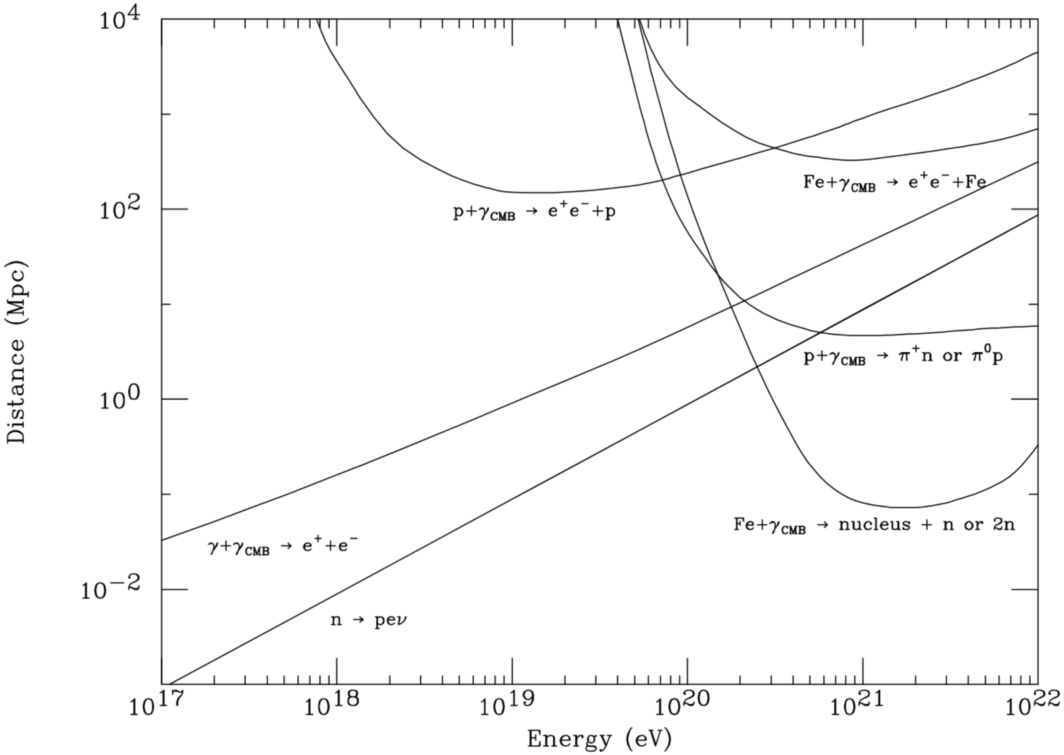
$$E_{\mathrm{p}^+} \approx 5 \times 10^{15} \mathrm{eV} \left(\frac{q}{e}\right) \left(\frac{m}{m_{p^+}}\right)^{-1} \left(\frac{B}{10\mathrm{G}}\right) \left(\frac{M}{M_{\mathrm{SgrA^*}}}\right)$$

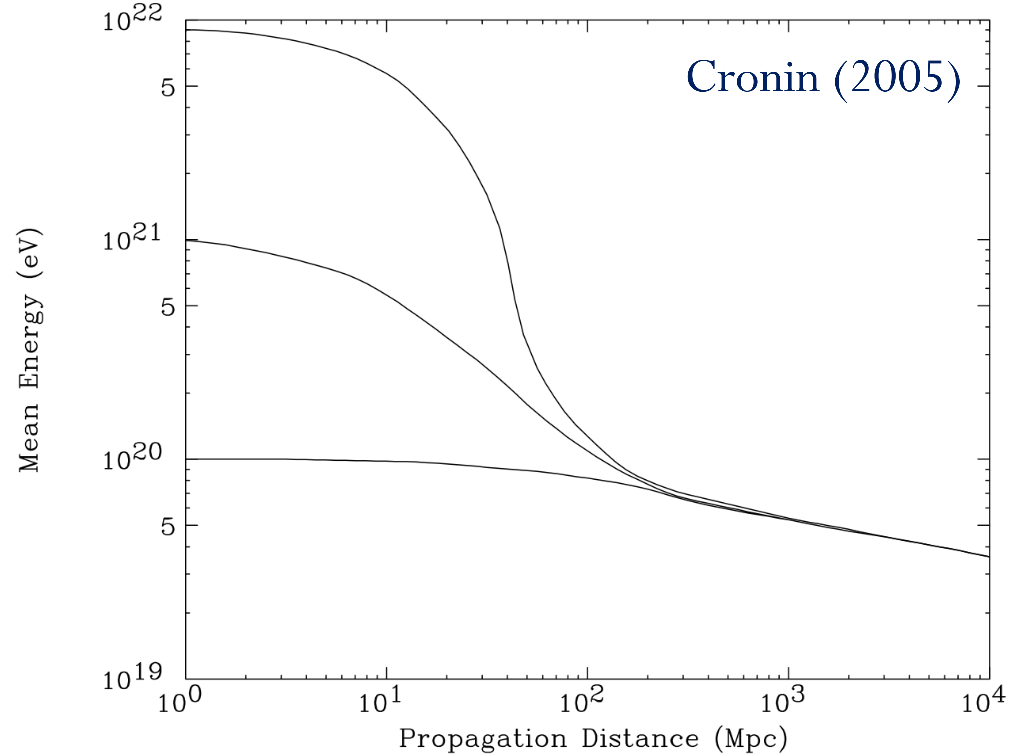
Tursunov et al., ApJ (2020)

Constraints on parameters and source candidates



GZK cutoff





left: Panorama of the interactions of possible cosmic primaries with the CMB; right: and mean energy of protons as a function of propagation distance through the CMB, based on GZK cutoff.

$$p + \gamma_{\rm CMB} \rightarrow p + \pi^0,$$

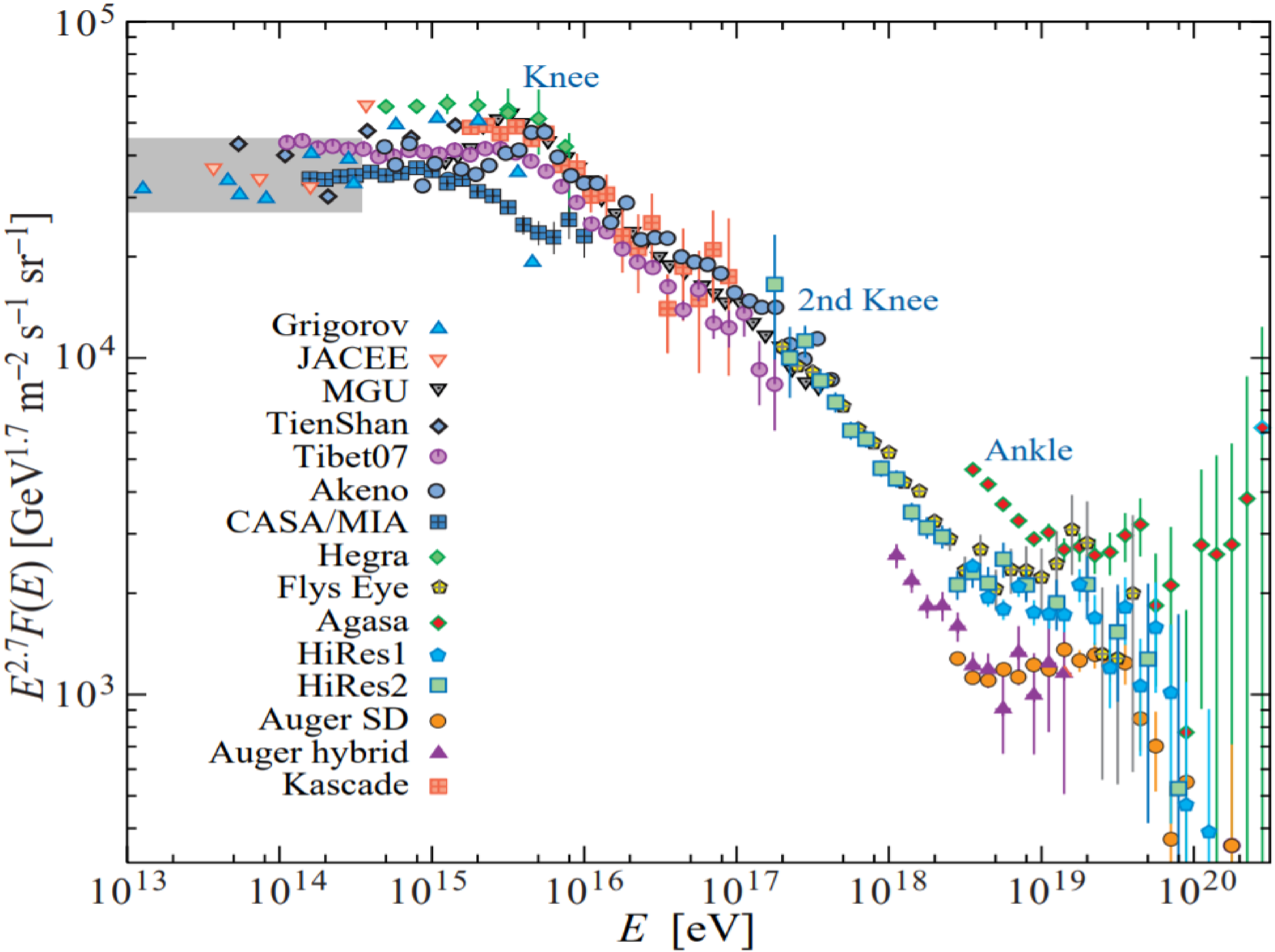
$$p + \gamma_{\rm CMB} \rightarrow n + \pi^+.$$

Collision of UHERCR proton with CMB produces 200 MeV in center-of-mass, which is the peak for photo-pion production

Selected nearby SMBH candidates

SMBH	$\mathrm{Log}(M/M_\odot)$	Spin a	d (Mpc)	$\mathrm{Log}(B/1\mathrm{G})$	$\mathrm{Log}\left(E_{p+}^{\mathrm{mean}}/1\mathrm{eV}\right)$
Sgr A*	6.63	0.5	0.008	2	15.64
NGC 1052	8.19	$\lesssim 1$	19	4.8	20.11
NGC 1068 / M77	6.9	$\lesssim 1$	15	4.54	18.56
NGC 1365	6.3	$\lesssim 1$	17.2	4.70	18.12
NGC 2273	6.9	0.97	29	4.58	18.41
NGC 2787	7.6	$\lesssim 1$	8	3.73	18.45
NGC 3079	6.4	$\lesssim 1$	22	4.06	17.58
NGC 3516	7.4	0.64	42	4.88	19.37
NGC 3783	7.5	0.98	41	4.15	18.77
NGC 3998	8.9	0.54	15	3.58	19.52
NGC 4151	7.8	0.84	14	4.6	19.53
NGC 4258 / M106	7.6	0.38	8	4.14	18.65
NGC 4261	8.7	$\lesssim 1$	32	3.51	19.33
NGC 4374 / M84	9	0.98	20	3	19.12
NGC 4388	6.9	0.51	18	5.19	19.11
NGC 4486 / M87	9.7	$\lesssim 1$	17	2.84	19.66
NGC 4579	8	0.82	18	4.11	19.23
NGC 4594	8.8	0.6	11	3.18	19.05
NGC 5033	7.2	0.68	20	4.47	18.77
NGC 5194 / M51	6.0	0.57	8	4.51	17.57
MCG-6-30-15	7.3	0.98	33	4.74	19.16
NGC 5548	7.8	0.58	75	4.48	19.34
NGC 6251	8.8	$\lesssim 1$	102	3.70	19.62
NGC 6500	8.6	$\lesssim 1$	43	3.60	19.32
IC 1459	9.4	$\lesssim 1$	31	3.20	19.72

All particle spectrum of cosmic rays



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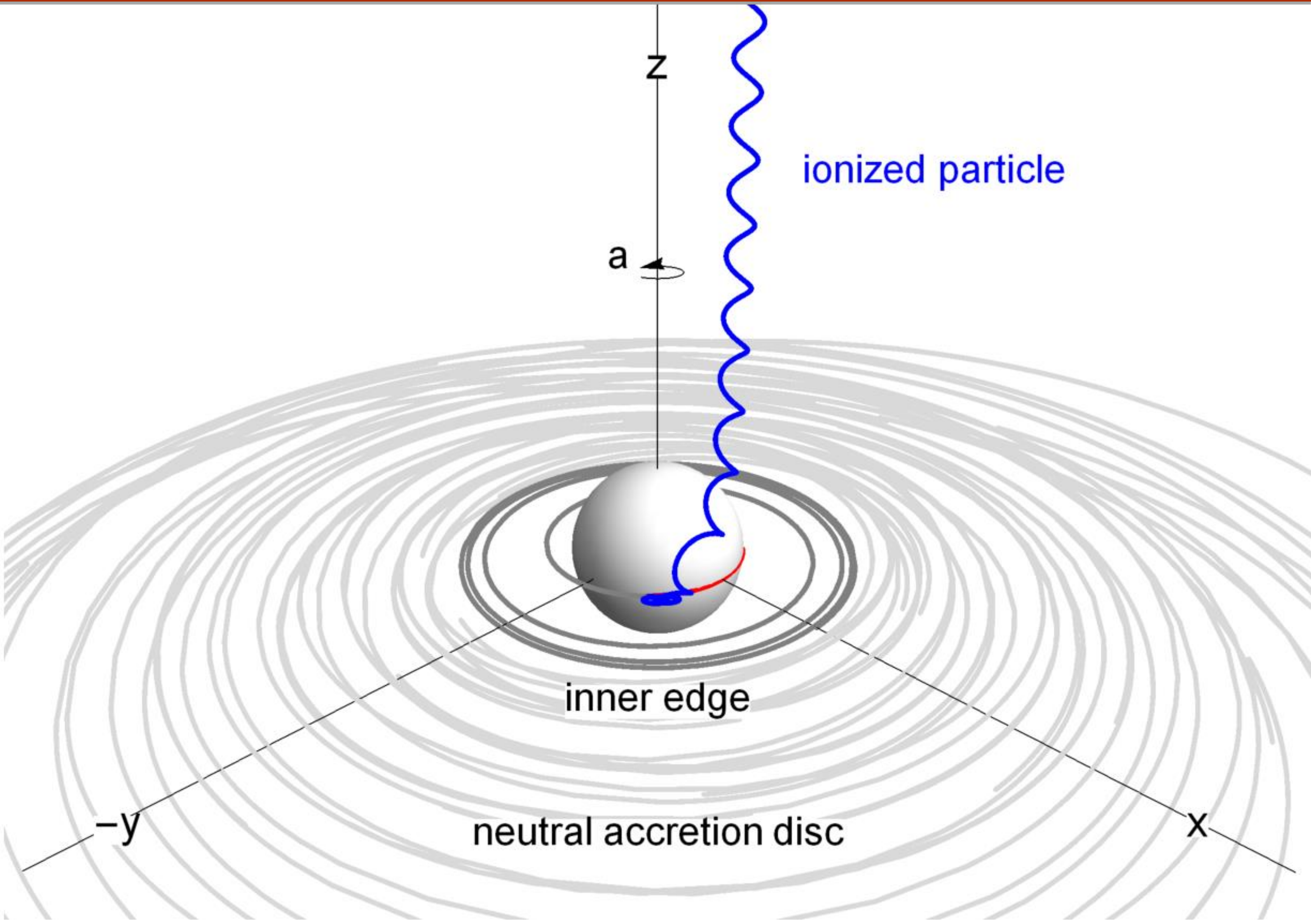
Energy extraction in various radioactive decay modes

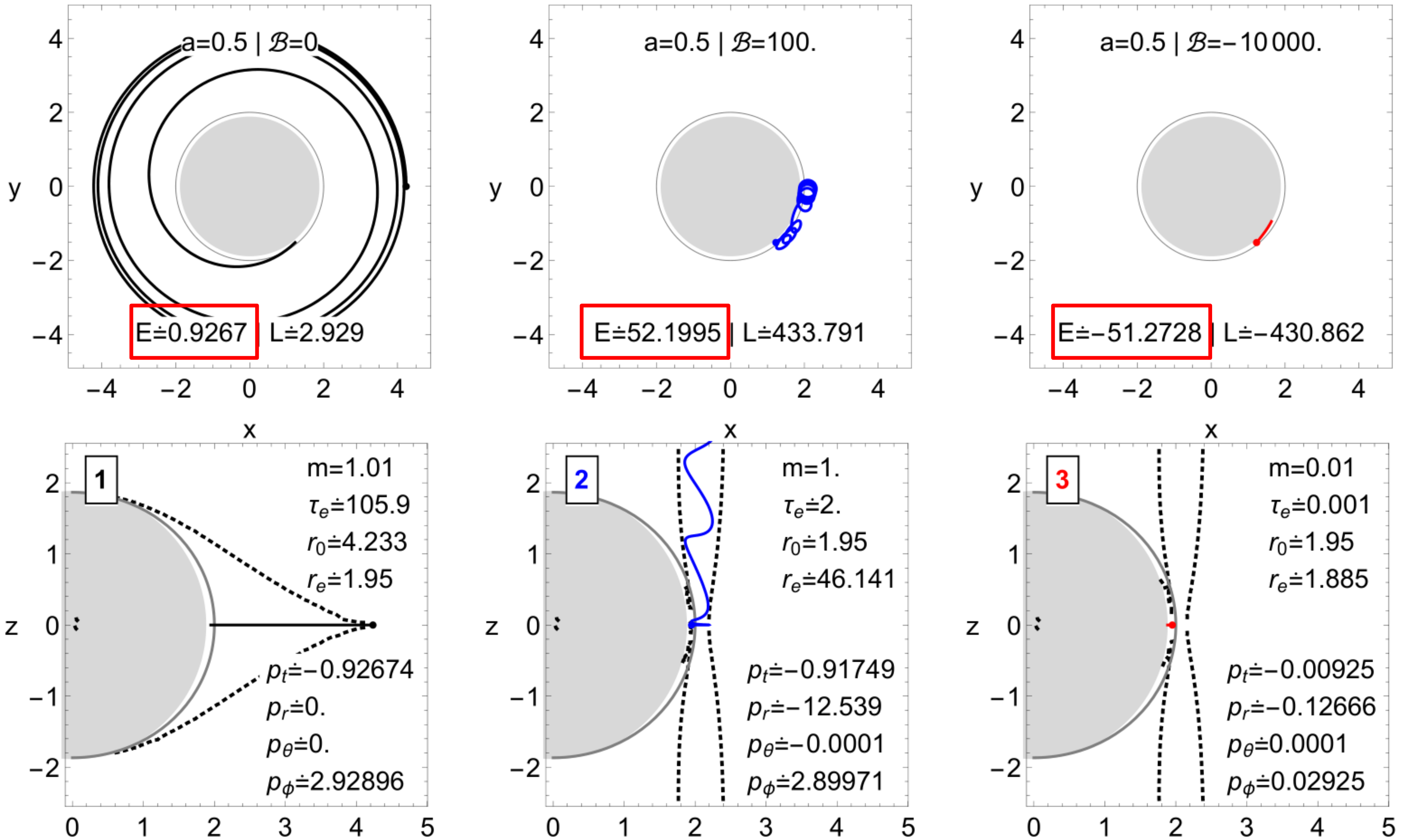
Decay Mode	Generic Equation	Esc. p.	Efficiency $\eta_{\max}$	Regime of MPP
α decay	${}^{A}_{Z}X^{0} \to {}^{A-4}_{Z-2}Y^{2-} + {}^{4}_{2}\alpha^{2+}$	Y	<0	-
		α	$1.2 \times 10^{6}/A$	ultra
	${}^{A}_{Z}X^{+} \to {}^{A-4}_{Z-2}Y^{-} + {}^{4}_{2}\alpha^{2+}$	Y	<0	–
		α	~ 1	moderate
	${}^{A}_{Z}X^{-} \to {}^{A-4}_{Z-2}Y^{3-} + {}^{4}_{2}\alpha^{2+}$	Y	~ 2	moderate
		α	< 0	-
β^{-} decay	${}^{A}_{Z}X^{0} \to {}_{Z+1}{}^{A}Y^{+} + e^{-} + \bar{\nu}$	Y	$6.1 \times 10^{5}/A$	ultra
		e^{-}	<0	–
		$\bar{\nu}$	0.06	low
β^{+} decay	${}^{A}_{Z}X^{+} \to {}_{Z-1}{}^{A}Y^{0} + e^{+} + \nu$	Y	<0	–
		e^{+}	~ 0	low/–
		ν	<0	–
γ emission	${}^{A}_{Z}X^{0} \to {}^{A}_{Z}X'^{0} + {}^{0}_{0}\gamma^{0}$	X′	0.06	low
		γ	0.06	low
Pair production	$\gamma^{0} \to e^{-} + e^{+}$	e^{-}	<0	–
		e^{+}	$5.5 \times 10^{8}/(2m_{e}c^{2})$	ultra

Efficiency of energy extraction from stellar mass black hole for various typical radioactive decay modes. Initial energy of decaying particle is taken to be equal to its rest mass.

Numerical modelling

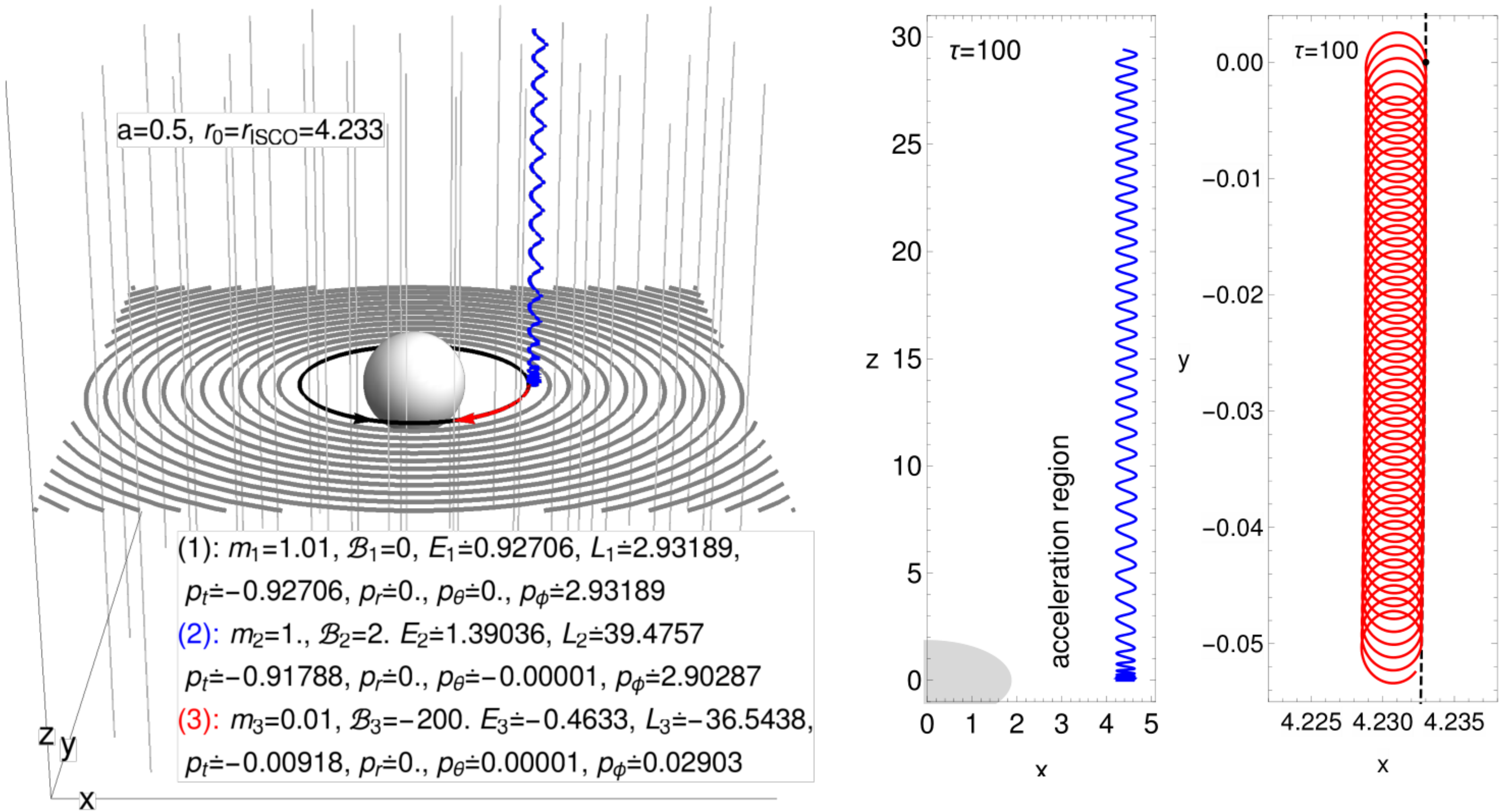


Numerical modelling



$$\mathcal{B} = \frac{|e|BGM_{\rm BH}}{m_p c^4} \approx 10^6 \frac{B}{10{\rm G}} \frac{M_{\rm SgrA*}}{10^{6.6} M_\odot}.$$

Numerical modelling



Role of BH charge!

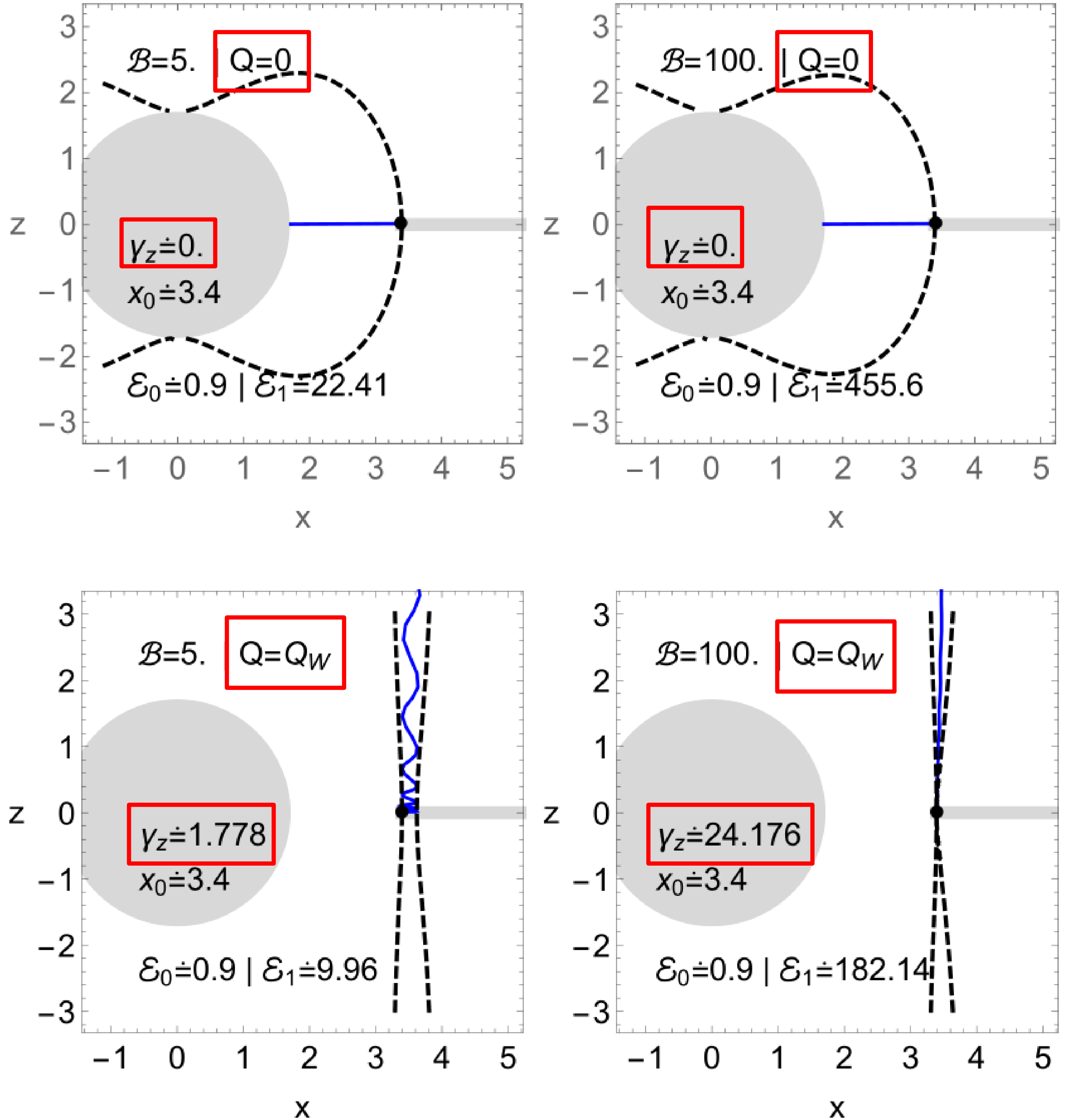
$$\mathcal{E} = \frac{E}{m}, \quad E_0 = E_1 + E_2$$

γ_z – factor of esc. par.

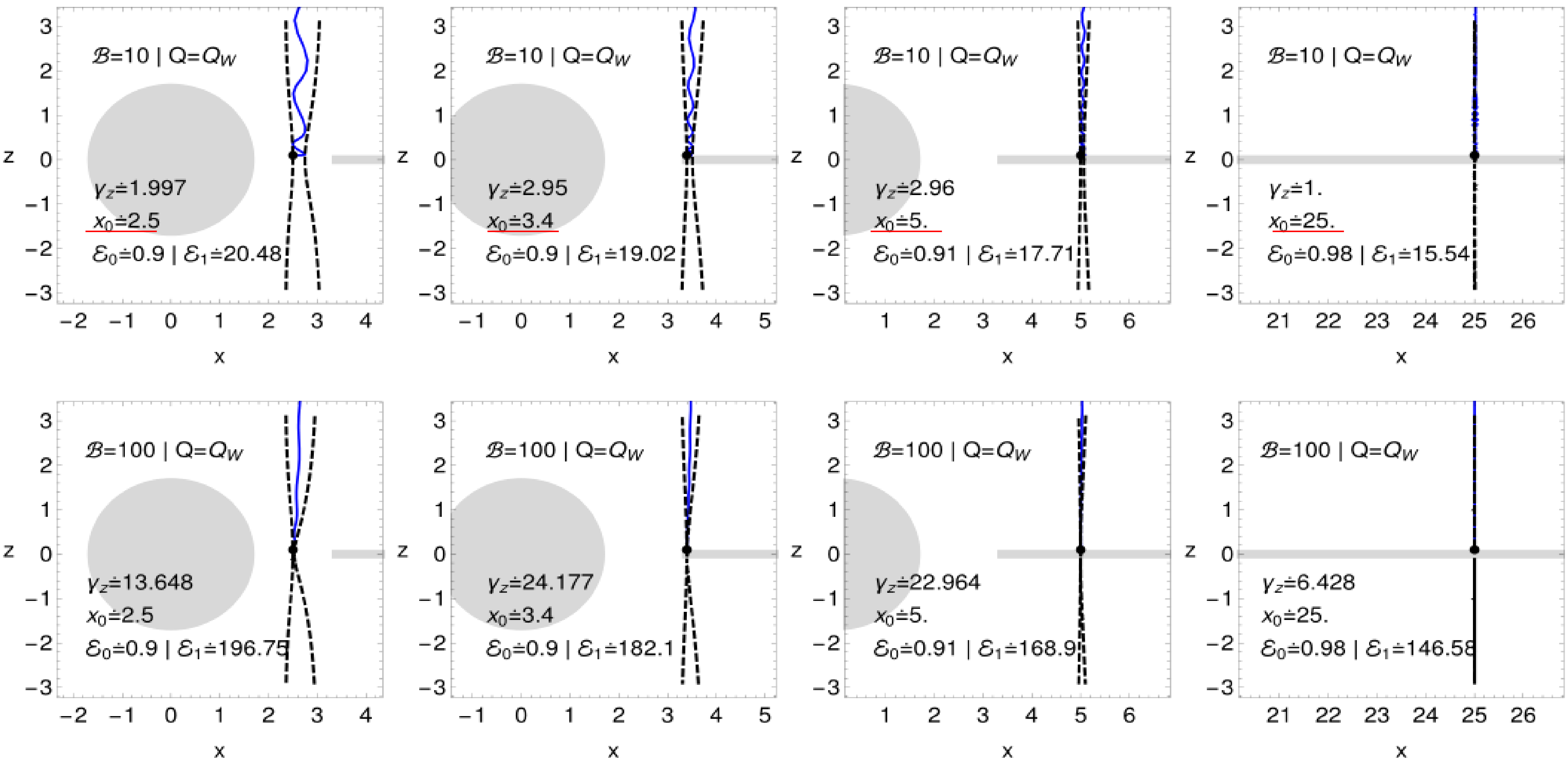
$$\mathcal{B} = \frac{|e|BGM_{\rm BH}}{m_p c^4}$$

$$\approx 10^6 \frac{B}{10\rm G} \frac{M_{\rm SgrA*}}{10^{6.6}M_\odot}.$$

Ionized particle escapes from BH only in the presence of induced net charge



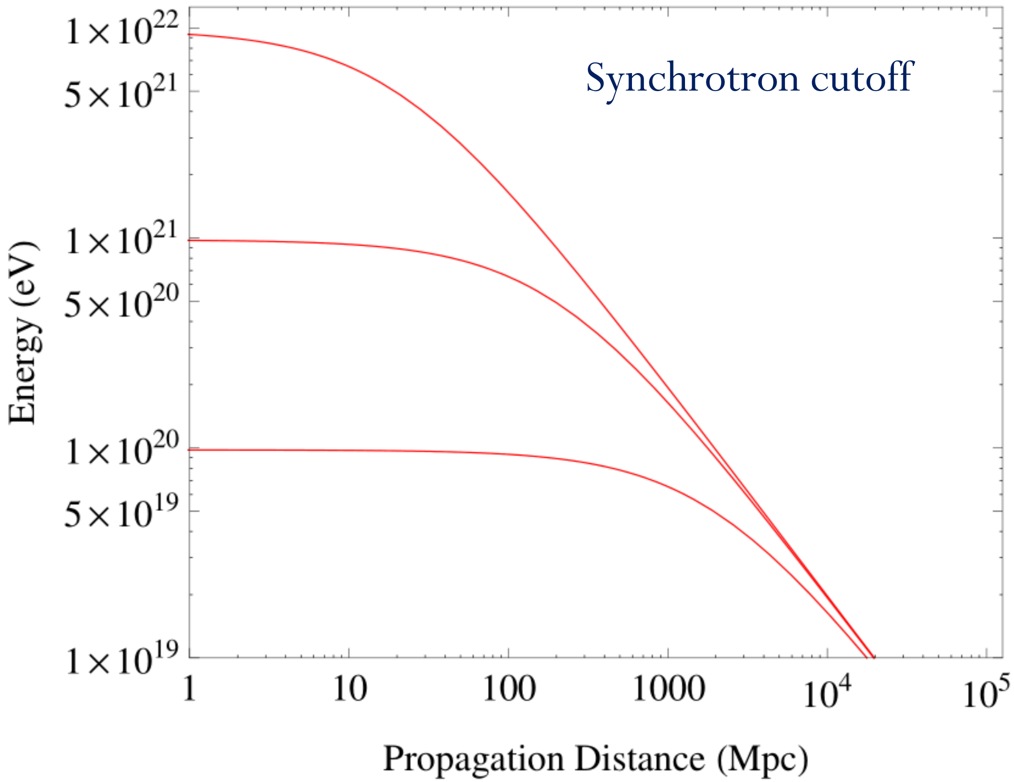
The process does not require existence of ergosphere!



Ionization may occur far away from the horizon, although the energy of ionized particle decreases with increasing the distance of ionization point from the BH. In contrast to competing mechanisms of energy extraction, the process does not require the existence of ergosphere.

Energy loss due to synchrotron radiation

Propagation of proton in equipartition magnetic field of order 10^{-5}G



$$\frac{d\mathcal{E}}{d\tau} = -2k\mathcal{B}\left[2\mathcal{B}\mathcal{E}^3 - \mathcal{E}\left(2\mathcal{B}f + \frac{u^\phi}{r}\right)\right].$$

$$\tau_{\max} \approx \frac{1}{k\mathcal{B}^2 f(r)}, \quad \mathcal{B} \gg 1$$

$$\mathcal{B}_{\rm SgrA^*} = \frac{|e|BGM}{2m_e c^4} \approx 1.86\times10^{10},$$

$$k_{\rm SgrA^*} = \frac{2}{3}\frac{|e|^2}{m_e GM} \approx 10^{-25}.$$

$$\frac{\tau_{\max}}{\tau_c}({\rm SgrA^*}) \approx 10^{-9}$$

B (Gauss)	τ_e (s)	τ_p (s)	$\tau_{\rm Fe}$ (s)
10^{12}	10^{-16}	10^{-6}	10^{-5}
10^8	10^{-8}	10^2	10^3
10^4	1	10^{10}	10^{11}
1	10^8	10^{18}	10^{19}
10^{-4}	10^{16}	10^{26}	10^{27}

Timescale of collisions of particles in plasma: $(T = 10^8{\rm K}, \quad n = 10^{14}{\rm cm}^{-3})$

$$\tau_{ee} \approx 6.4\times10^{-4}{\rm s}, \quad \tau_{ei} \approx 4.5\times10^{-4}{\rm s}, \quad \tau_{ii} \approx 4\times10^{-2}{\rm s}.$$

Neutron stars are also ruled out due to large synchrotron loses of protons in strong MF of NSs.

General relativistic covariant equation of motion

$$\frac{Du^\mu}{d\tau} = \frac{q}{m} F^\mu{}_\nu u^\nu + \frac{2q^2}{3m}\left(\frac{D^2 u^\mu}{d\tau} + u^\mu u_\nu \frac{D^2 u^\nu}{d\tau}\right)$$
$$+\frac{q^2}{3m}\left(R^\mu{}_\lambda u^\lambda + R^\nu{}_\lambda u_\nu u^\lambda u^\mu\right)$$
$$+\frac{q^2}{m} u_\nu \int_{-\infty}^{\tau} D^{[\mu} G^{\nu]}_{+\lambda'}(\tau,\tau') u^{\lambda'}(\tau')\, d\tau'.$$

- **Neutral geodesics**
- **Charged particles**
- **Backreaction SR**
- **Backreaction GR**

(DeWitt and Brehme 1960)

- Ricci terms are irrelevant in vacuum metrics
- Tail term can be estimated, e.g. around Schwarzschild BH as $F_{\rm tail} \sim \frac{GMq^2}{r^3 c^2}$.

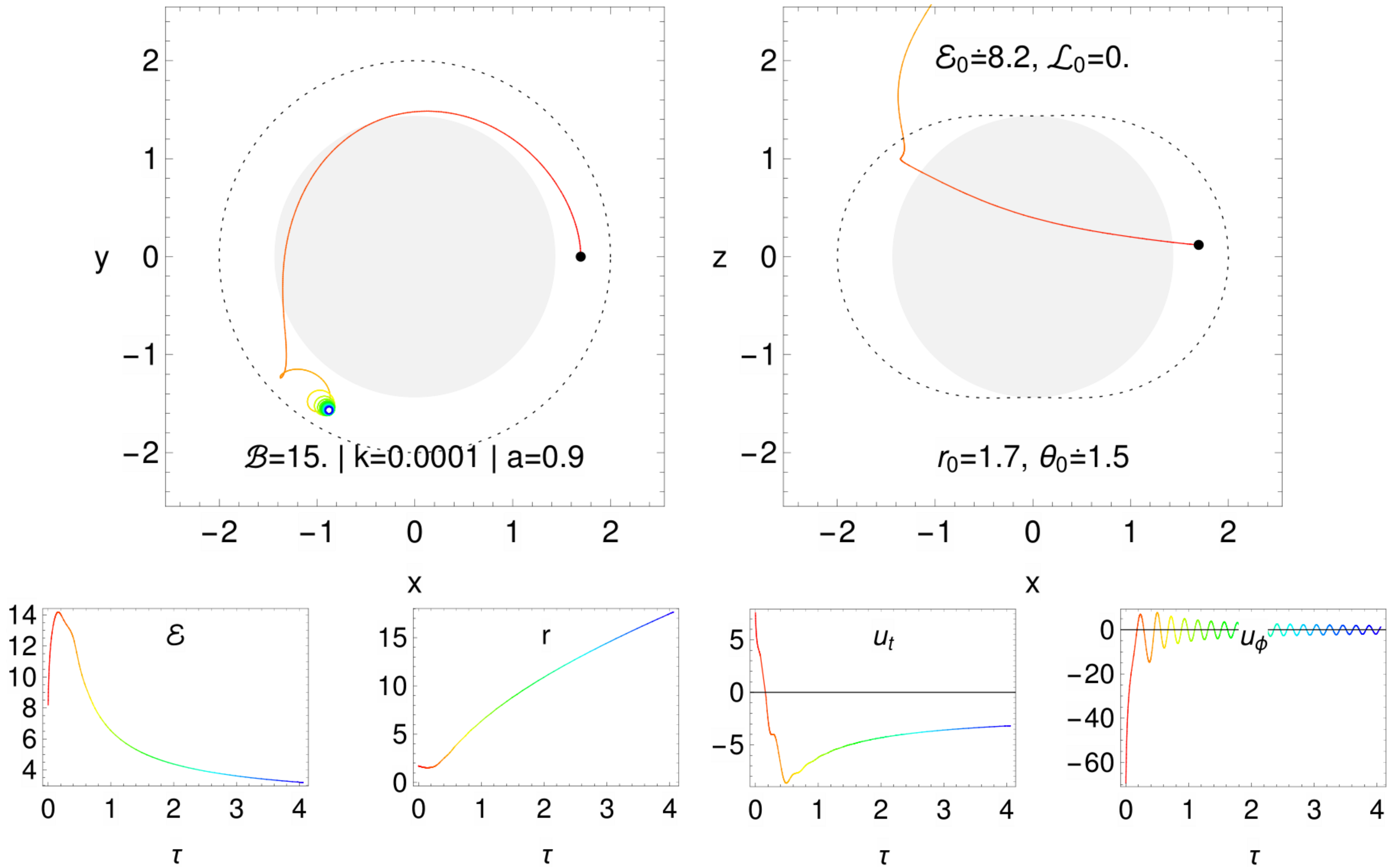
$$\frac{F_{\rm tail}}{F_{\rm N}} \sim \frac{q^2}{mMG} \sim 10^{-19}\left(\frac{q}{e}\right)^2 \left(\frac{m_e}{m}\right)\left(\frac{10 M_\odot}{M}\right)$$

e.g. Dewitt & Dewitt (1964), Smith & Will (1980), Gal'tsov (1982), …

- Radiation-reaction term can be estimated as $F_{\rm RR} \sim q^4 B^2/(m^2 c^4)$

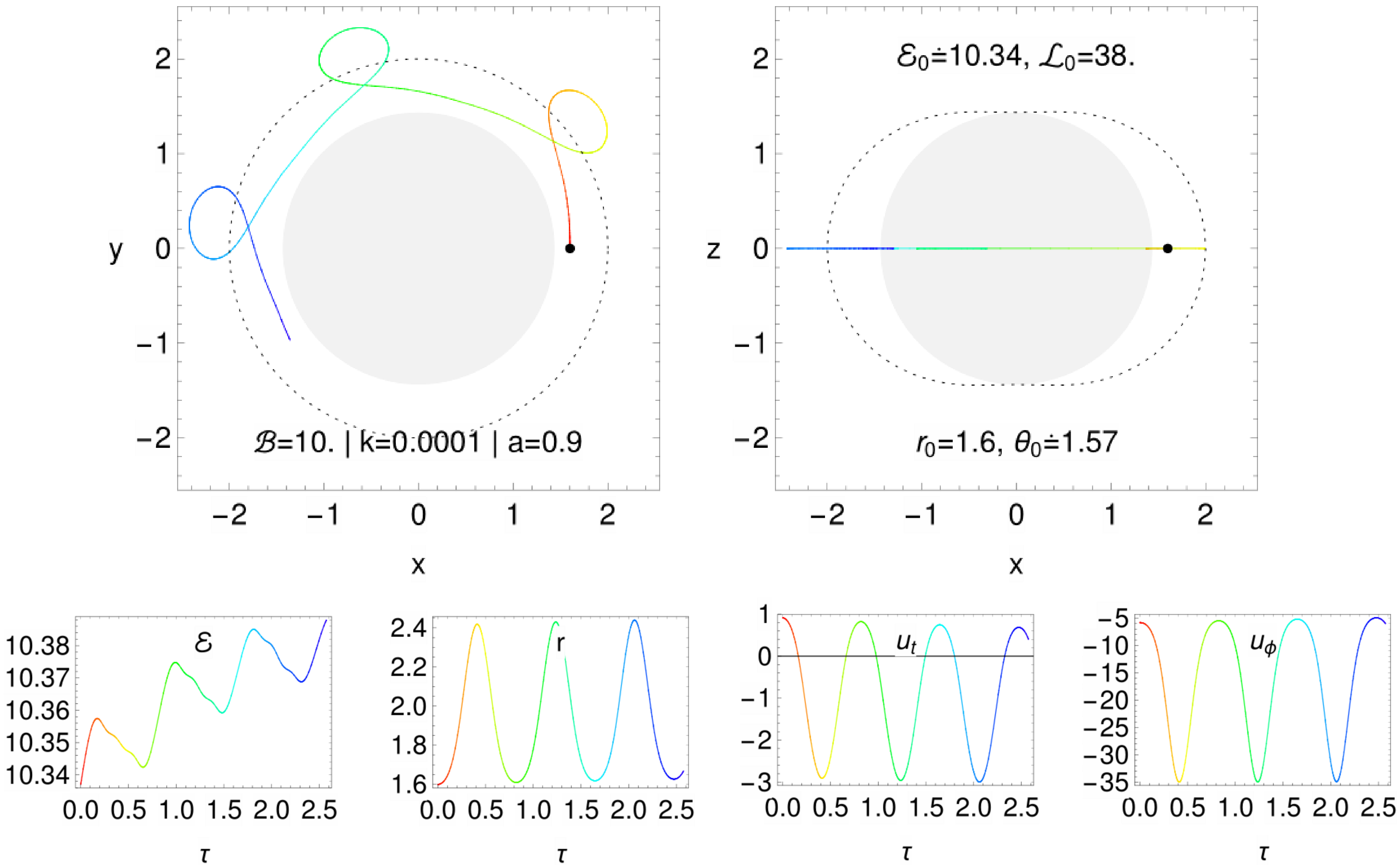
$$\frac{F_{\rm RR}}{F_{\rm N}} \sim \frac{q^4 B^2 M G}{m^3 c^8} \sim 10^3 \left(\frac{q}{e}\right)^4 \left(\frac{m_e}{m}\right)^3 \left(\frac{B}{10^8 {\rm G}}\right)^2 \left(\frac{M}{10 M_\odot}\right)$$

Energy extraction by a single particle: Radiative Penrose Process



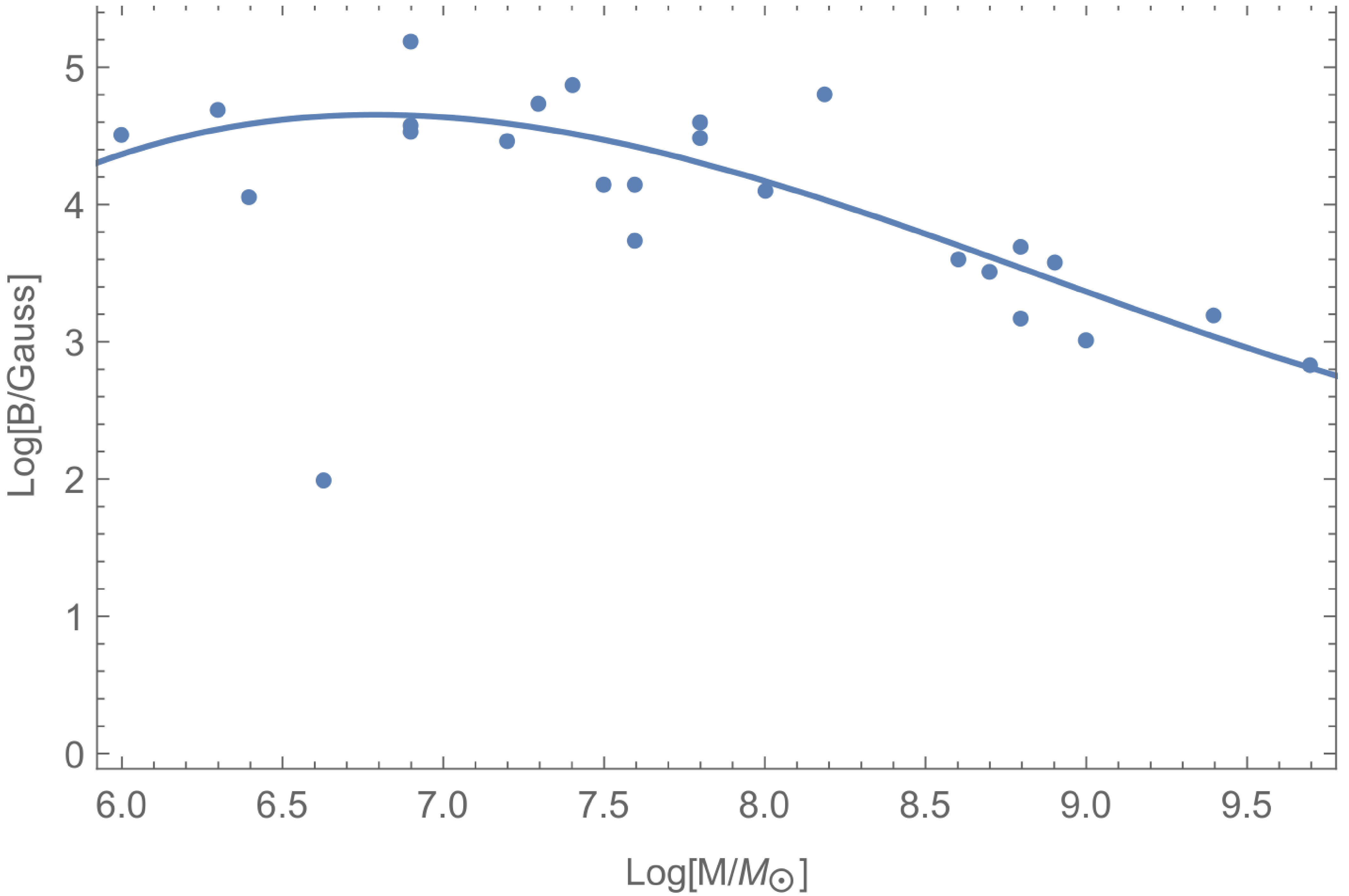
More details: talk by Martin Kološ on Wednesday at 10:45

Energy extraction by a single particle



Higher energy emission from the edge of the ergosphere

Magnetic field – Mass correlation



Summary

Required ingredients for the black hole energy extraction:

- Rotating BH & magnetic field
- Negative energy inflow into BH:
  - either due to electromagnetic interaction of charged particle with BH
  - or geometric effect in the ergosphere
- **Required ingredients for escape to infinity:**
- Sharing symmetries of BH and magnetic field lines
- Induced BH charge (Wald mechanism)

Main advantages & predictions of the model:

- The model predicts SMBHs as the source of highest-energy cosmic rays
- Provides verifiable constraints on Mass and B-field of the SMBH candidate to produce UHECRs
- Operates in viable astrophysical conditions for SMBH with moderate spin and MF strength
- Does not require extended acceleration zone (jet models), nor the fine-tuning of parameters
- Energy extracting action can take place relatively far rom the event horizon without high redshifts
- Galactic center can act as a PeVatron of cosmic rays and contributes to the knee of the CR spectra
- Radiative mechanism predicts higher I of non-thermal radiation from the edge of the Ergosphere